

STUDIES ON WEATHERING AND SOIL
FORMATION IN TROPICAL
HIGH ALTITUDES

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By M. W. SENSTIUS

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SYNOPSIS

THE investigations reported upon in the following pages were undertaken to test the validity of modern conceptions of soil-formation, or rock-weathering in the wider sense, in the Oriental tropics.

These modern conceptions and their historical development are reviewed in Chapter I.

Briefly summarized the prevailing idea in modern agrogeology is that the soil is a function of the climate, and particularly of the climatic factors temperature and humidity. The nature of the parent rock is considered of secondary importance; it may impress its characteristics upon the resulting soil only so long as the latter is not mature ("Azonal" soils according to Dokuchaiev and Sibirtzev, "endodynamomorphic" soils according to Glinka, or "Ortsböden"—local soils—according to Ramann). In the mature stage of soil formation, however, the characteristics of the parent material have become obliterated and the resulting soils are expressions of the prevailing climates, in other words, the same climate produces the same general soil-characteristics, irrespective of the soil-forming parent materials.

The following investigations are mainly concerned with those mature soils which have been variously termed, by the originators of these modern conceptions, "Zonal" soils (Dokuchaiev and Sibirtzev), "ectodynamomorphic" soils (Glinka) and "Climatic" soils (Ramann). They will henceforth be referred to as climatic soils or major soil groups.

The direct stimulus for the inquiry came from reading E. C. J. Mohr's treatise on "The Soils of Java and Sumatra" (in Dutch, Amsterdam, 1922). In this book, the result of some twenty-five years of soil-studies in the Netherlands East Indies, the author has shown that the leading principles of modern views on the relation between climate and rock-weathering, respectively, soil-formation, are well demonstrated in that part of the Eastern tropics.

A summary of his ideas is given in Chapter II. But neither in the aforementioned book, nor in his other writings has Mohr substantiated

*This paper was awarded the Walker Prize for 1929 by the Boston Society of Natural History.

his views with analytical data. Subsequent search in the literature for such pertinent information revealed its total absence.

The ideas, however, are rationally sound and of farreaching importance in their possible application to other tropical regions. It was therefore considered worth while to independently investigate the question both in the field and in the laboratory. It was argued, furthermore, that if Mohr's views are correct, his findings should be capable of confirmation in similar regions as far to the north of the equator as his field of observations was to the south of the equator. Hence the field-work was carried out both in the Netherlands East Indies and in the Philippine Islands, or specifically, on the islands of Java (N. E. I.), Negros and Luzon (P. I.).

Chapter III states the problem more specifically and also describes the methods of investigation in the field and in the laboratory.

Chapter IV discusses and summarizes the results obtained.

CHAPTER I

DEVELOPMENT OF OUR MODERN CONCEPTIONS OF WEATHERING AND SOIL FORMATION

EVERYBODY knows what a soil is although no one, as yet, has been able to define a soil in terms that are wholly acceptable to every one else. Agronomists have one definition, or rather a number of definitions differing in minor details, and so have geologists; it would serve no useful purpose to enumerate them here. But agronomists and geologists alike agree at least that a soil, essentially, is made up of mineral fragments which are more or less loose and were derived, by processes of weathering, from rocks, which themselves may have been solid or fragmental at the start. This mineral matter is usually mixed with more or less organic matter and water, besides air.

The obvious fact that most soils are essentially derived from rocks has led the earlier soil-investigators—be they geologists or agronomists—to build up a soil-classification on the basis of the parent-rock. Thus they spoke of limestone-soils, granite-soils, basalt soils, etc. Or else, they based their classification on the geological formation which gave rise to the

particular soils, etc. These classifications which have persisted more or less to this day are rather fully discussed in Glinka's book¹ to which reference may be made. They originated in earlier times when investigators were largely confined to more or less local observations in areas of small extent—mostly in their own neighborhood—due to the lack of the proper means for traveling far and wide from their immediate surroundings.

As traveling became easier and more scientists could embrace large areas of the earth in their explorations, they could not fail to notice that in many parts the soils were remarkably the same over extensive areas, irrespective of the parent-rock from which they were derived. Thus they found, as a rule, in the tropical lowlands, that the soils were dominantly red in color in spite of the fact that the parent-rock showed a great diversity of composition, such as basalts, gneisses, granites, limestones, shales, etc. In other parts of the earth, in the colder climates near the poles or in high latitudes, they noticed that the soils were dominantly light in color, light-gray to white, underneath a more or less thick layer of humus,—again irrespective of the rock which gave rise to these soils.

It was then that some enlightened scientists turned to the processes of soil-formation, *i.e.*, the weathering of rocks, as a possible basis for a classification of soils.

Rock-weathering refers to the action upon rocks of the weather, or, in a larger sense, of the climate, as being the average of weather-conditions over a more or less prolonged period of time. These considerations led to our more modern climatic classification of soils, a natural and genetic classification which promises to become the foundation upon which the superstructure of the whole study of the soil is to rest, in much the same way as the natural classification of plants or of animals has become the starting point for any study in botany or zoology.

¹ The numbers refer to the numbered items of the bibliographical list at the end of this paper.

It has been suggested that these modern ideas were the result of the study of soils over extensive areas on the earth, viewed as a whole in their main characteristics. One should not wonder, then, that Russian scientists were among the first, if not actually the first, to recognize the leading principles. Theirs was a country at once vast and with a great diversity of climatic conditions. To one of them, viz., the geologist Dokuchaiev fell the privilege of extensive traveling in this great country of Czarist days during the second half of the last century. Keen observer that he was, Dokuchaiev did not fail to notice that in Russia, as the climates differed according to latitudinal belts or zones, extending, roughly speaking, in a West-East direction, so did the major soil-characteristics differ with the climates from zone to zone. Thus he conceived of the zonal distribution of soils, of the zonality of soil-regions, coinciding with climatic zones, and he became the first to attempt (1879) a natural soil-classification based on climatic agencies of weathering and soil-formation.² Dokuchaiev was also the first to demonstrate its practicability in the actual mapping and evaluation of soils, viz. of the Government of Nijni-Novgorod (1887), then of the Government or Province of Poltava (1890-1894) and subsequently of other provinces in Russia.³ In this work he was ably assisted by students who subsequently carried on the work of their master, elaborating and improving it until today the Russian pedologists are unquestionably the leading and most successful exponents of the newer ideas referred to above.

Extensive travels in many parts of the earth caused another geologist and geographer, this time the German scientist von Richthofen, as early as 1886 to pronounce the statement that "the soil is mainly a function of climatic agencies."⁴

And in the United States of America it was particularly E. W. Hilgard who apparently came independently to the conclusion (1892) that climate plays a very important role in determining soil characteristics. If for nothing else he will always be remembered as the first one who clearly pointed out the differences between soils that originated in humid climates and those which originated in arid climates.⁵

It may be recalled that Hilgard, for many years had taught and worked in the State of Mississippi and at the University of Michigan. He thus became thoroughly acquainted with the characteristics of the soils of the humid section of the United States. But it was not until he had gone to the University of California, there to study the soils of the arid and semi-arid West, that he made his classical contributions in the realm under discussion.

The three scientists referred to above, who were all geologists at the start, may be regarded as the founders of our modern conceptions concerning the relation between climate and soil formation, respectively soil-characteristics, although they had some forerunners. Treitz,⁶ for instance, states that the Russian, G. Tolstoj, in 1855, and the Austrian, L. von Liburnau, in 1866, had expressed kindred ideas. These ideas, however, do not seem to have been the starting-points for much further development, so that the real credit for having stimulated a great many workers to productive research along the new lines should still be given to Dokuchaiev, von Richthofen and Hilgard.

Their work has been amplified and extended by a host of agro-geologists or pedologists in almost every civilized country. A partial list of the most outstanding workers would include the names of Sibirtsev and Glinka in Russia; Ramann, Richard Lang and Stremme in Germany; von Leiningen and Kerner von Marilaun in Austria; Treitz in Hungary; Murgoci in Roumania; Miklaszewski in Poland; Hesselman, Tamm and Simon Johansson in Sweden; Aarnio and Frosterus in Finland; Hissink and van Baren in the Netherlands; Mohr in the Netherlands East Indies, and a large number of soil-scientists under the leadership of Marbut in the United States.⁷

As a result of their work, Dokuchaiev's original scheme has been modified and improved upon, though by no means radically. Glinka has recently given a summary of the various Russian systems of soil-classification together with a profound discussion of his own.¹ Since this work is now available in the English translation by Marbut it may suffice to refer to that source of fundamental information.

Other notable contributions have been made, particularly by Ramann and Lang, to which reference may be made here.⁸

In spite of the relatively large number of soil-scientists who are now actively at work in various parts of the earth, one should not expect the scheme to be complete, inclusive and comprehensive as yet. Pedology or agro-geology as an individual branch of science is still too young and workers are too few or entirely lacking in many critical regions.

This is particularly the case within the tropics, both Oriental and Occidental tropics.

Although countless contributions have been made toward the knowledge of tropical soils, yet, with few exceptions, they lack the necessary unified viewpoint that would enable one to survey tropical soil-characteristics as a whole. One notable exception is due to the work of the Dutch agro-geologist E. C. Julius Mohr in the Netherlands East Indies and particularly on the island of Java. The physiographic configuration of the island of Java, its macro-relief, has led Mohr to the recognition of vertical zonality in addition to the previously established horizontal zonality of rock-weathering and soil-formation. The rationale of these conceptions has been clearly stated by Mohr in the year 1913,⁹ and subsequently elaborated in 1922.¹⁰

It is true that according to Glinka (*op. cit.*, 2b, pp. 15-16), Dokuchaiev and some of his pupils had previously expounded kindred ideas in a series of articles in Russian which date back as far as the year 1898. There is no indication, however, that Mohr had any knowledge of their writings, or of their work. At any rate he may be safely considered as being the first to have rationalized the vertical zonality of climatic soil types in the tropics.

Mohr's ideas, which were published in the Dutch language, shared the fate of those of his Russian precursors: they remained unknown outside of their native country, viz. the Netherlands East Indies and Holland.

On account of their fundamental importance, and because they were the starting point for the author's own investigations, to be reported upon presently, Mohr's ideas are reviewed at length in the following chapter.

CHAPTER II

MOHR'S IDEAS CONCERNING THE RELATION BETWEEN
CLIMATE AND SOIL FORMATION OR ROCK-
WEATHERING IN THE TROPICS

It has been indicated that Mohr developed the conception of vertical zonality of tropical soils as a result of his work, particularly in Java.

Java is a narrow and elongated island, lying almost parallel with the equator between latitudes 6° – 8° South. A chain of young volcanic mountains of late Tertiary age extends through its longer axis from West to East. Its individual peaks, some of which are still active, reach elevations up to 3,676 meters (12,000 feet) and the island shows a great variety of topographic relief forms.

Java forms part of a world of islands, the Malay Archipelago, in which the bodies of water occupy about 84 per cent. of the total area. The marine influence on the climate is consequently most pronounced, and, together with the location so near the equator, has caused Java to possess an extremely equable climate. This is expressed in almost negligibly small ranges of temperature, both annual and diurnal.

Thus in Batavia, at 8 m. above sea-level, the average annual range of temperature is only 1° C. and the average daily range is 7.3° C. The values for Buitenzorg at 240m. are respectively 1.2° C. and 8.1° C.; Bandoeng at 730 m. has respectively 0.6° C. and 9.3° C., while the Dieng-Plateau at 2100 m. has 1.6° C. and 7.1° C. respectively.

In this equable climate the average temperature is largely a function of the elevation above sea-level, decreasing by about 0.56° C. for a rise of 100 m., so that zones of temperature may be recognized something like the following (see Table 1):

The *first* zone, occupying the hot tropical, or rather the equatorial lowlands up to about 200 meters, has practically no temperatures lower than 20° C. and its average temperature of about 25° C. is found in the soil as a constant temperature at a depth of less than one meter. The temperature of this

TABLE I *

ELEVATION		AVERAGE TEMPERATURE		MINIMUM TEMPERATURE		MAXIMUM TEMPERATURE	
Meters	Feet	° C.	° F.	° C.	° F.	° C.	° F.
0	0	26.5	80.0	25.0	77.0	33.0	91.0
200	600	25.0	77.0	20.0	68.0	30.0	86.0
1,000	3,000	20.0	68.0	15.0	59.0	25.0	77.0
1,800	6,000	15.0	59.0	10.0	50.0	20.0	68.0
2,600	8,500	10.0	50.0	5.0	41.0	15.0	59.0
3,400	10,000	5.0	41.0	0.0	32.0	10.0	50.0
4,300	14,000	0.0	32.0	SNOW LINE		SNOW LINE	

* (This table represents average air-temperatures. But owing to the fact that the temperature-ranges are so small, it may be taken as representative of the soil temperatures as well.)

zone offers the best conditions for the cultivation of the low-land cultures such as rice, sugar-cane, tobacco, and most of the land in this zone is used for growing these crops.

The *second* zone, moderately warm, from 200–1,000 m. which may be called the equatorial hill-lands, has no temperature over 30° C.; the average temperature decreases to 20° C. At 1,000 m. the upper limit of successful coconut growing is reached and the wet rice fields of the lowlands also disappear. Tea and coffee can well be grown here, so far as quantity production is concerned, but for the best flavor one has to go still higher, viz., to the *third* zone, from 1,000–1,800 m. in elevation, which may be termed the equatorial highland zone. Here the temperature never reaches 25° C. and the average is only 15° C. at its higher limit. Palm trees no more grow here, but the primeval forest vegetation is especially dense with mosses, ferns and orchids growing on the trees, lianas hanging down from the trees, and dense underbrush covering the ground. Here are raised cinchona, European vegetables, roses of the temperate climates, but banana trees have disappeared.

The *fourth* zone, above 1800 m. in elevation, which may be designated the equatorial high-mountain zone, comprises only small areas, mostly the steep higher slopes of the mountains and a few high plateaus. The primeval forests gradually

become lower in height and less dense, until they finally dwindle down to low brushwood with grasses. Mosses still constitute an important part of the vegetation, but above 3,000 m. practically all the vegetation has disappeared.

It may seem strange that in a discussion of soils so much attention should be paid to the vegetation. It may be justified, however, on the ground that if such relatively small variations in temperature can bring about such great differences in the macro-flora, we might well suppose similarly great differences to exist in the micro-flora, especially in the micro-organisms living on and in the soil. It is well known, for example that many species of bacteria only begin to grow well and to multiply most rapidly above 30° C.; at 20° C. their growth is appreciably arrested and becomes practically nil between 15° C. and 10° C. The higher plants, on the other hand, have a much lower optimum temperature. The significance of these considerations will be shown presently.

The rainfall of Java, which is under the influence of the monsoon-winds, is high all the year in certain parts, periodically high and low from season to season in other places, and in still others may be constantly low. (In general it may be said that the precipitation decreases as we go eastward.) Accordingly, with respect to the moisture conditions, the following three cases can be distinguished as bearing directly on soil formation:

- (1) Regions where the precipitation constantly exceeds the evaporation. $P > E$.
- (2) Regions where during part of the year (wet season) precipitation exceeds evaporation, and evaporation exceeds precipitation during the remainder of the year (dry season). $P \geq E$.
- (3) Regions where the precipitation is constantly less than the evaporation. $P < E$.

The significance of these distinctions will be spoken of again presently.

A combination of the temperature zones with these humidity provinces gives twelve possible cases; in reality five of

them are non-existent in Java. For in the highland and high-mountain zones it never happens that, for any length of time, evaporation exceeds precipitation; hence four possibilities automatically drop out. In the hill lands it may sometimes happen that the dry monsoon is quite pronounced, but it is always followed by a rainy season, so that continuous excess of evaporation over precipitation never occurs here.

There are, then, only seven possibilities to be reckoned with, indicated by the + sign on the following table.

TABLE 2

ELEVATION	DESIGNATION	$P > E$	$P \geq E$	$P < E$
0-200 m. (0-600 ft.)	Lowlands	+	+	+
200-1,000 m. (600-3,000 ft.)	Hill lands	+	+	-
1,000-1,800 m. (3,000-6,000 ft.)	High lands	+	-	-
> 1,800 m. (6,000 ft.)	High mountain lands	+	-	-

It is being more and more recognized that in a mature natural, undisturbed, residual soil the nature of the parent rock plays a subordinate role. But for completeness' sake it may be stated that the underground of Java consists of geologically recent formations. These are mainly composed of sedimentary rocks—such as limestones, sandstones and conglomerates and breccias of basic igneous rocks—besides an abundance of recent igneous rocks, such as diorites, diabases and gabbros among the oldest rocks, and andesites and basalts among the youngest. All of them, then, are basic igneous rocks, *i.e.*, contain a large amount of lime and ferro-magnesian minerals, which weather readily. Since, moreover, the recent and numerous volcanic eruptions have mostly been of the violently explosive type, the soil everywhere contains pyroclastics of these basic igneous rocks in its mass.

The significance of the ratio between precipitation and evaporation in the processes of weathering, soil formation and transformation has been most clearly brought out by Hilgard.⁵

Where the precipitation exceeds the evaporation, a constant downward movement takes place of the water in the

soil, provided texture and structure of the soil permit any percolation. This effects a carrying downward and away of the soluble mineral substances, a leaching out of the soil. The soil-water, thus carried away, does not only take mineral substances into solution, but organic matter as well, more or less organic matter according to the richness of the vegetation on top.

When the evaporation exceeds the precipitation, then, the rainwater may temporarily soak into the soil for a few inches or more, only to be drawn up to the surface again and evaporated, as a result of which any dissolved material is deposited on top or near the top.

In the first case the soil is made poorer by leaching, in the second case the soil is enriched by concentration.

In the intermediate case, when $P > E$ during part of the year and $E > P$ during the remainder, there will be downward leaching to greater depth followed by upward enrichment, the one process alternating with the other.

It was said a little while ago: "provided soil texture and structure permit of such movements." Textures and structures may be:

(1) very coarse and pervious for water. If so, then, even in the case when $P > E$, part of the rainwater will move downward but cannot go up again, due to the small capillary action and the movement will be continuously downward, or intermittently downward at best;

(2) or, the soil may be fine-textured and pervious. Then, the movement of the percolating rainwater under conditions of $P \geq E$ will be alternately downward and upward.

(3) in the third place, the soil may have a very fine texture, such as is possessed by clay for instance, and be impervious, but exhibit only high water-capacity. In such a case, when $P > E$ the soil will fill up with moisture, but at the same time, will permit of little downward movement; when $P < E$ this soil is likely to dry out and form cracks, but still without much movement of water from below upward.

Thus it comes about that where $P > E$, leaching at times

takes place at an enormous rate, at other times is quite small. Or again, when $P > E$, soil texture and structure sometimes may bring about intermittent leaching, sometimes an equilibrium between leaching and enrichment.

Before proceeding any further with the different combinations of temperature and water-movement, it is well to consider first the relation between the temperature and the vegetation, spoken of a while ago.

It is well known that microscopic organisms, in general, have a higher optimum temperature than have the higher plants. The lower limit of temperature for the growth of higher plants is reached somewhere around 0°C ., as is exemplified by certain Alpine plants which pierce their flowers through snow and ice in the beginning of the Spring season; the upper limit lies around 45°C . or 115°F ., as in the case of desert plants, and the optimum temperature is about 25°C . or 77°F .

For micro-organisms, however, these limits are different; at 15°C . or 61°F . their life activities are little intense, and at 10°C . life activities and growth have practically ceased; their optimum temperature, accordingly, is much higher than 25° – 30°C ., indeed it is as high as 35° – 40°C ., while some micro-organisms may live and thrive well in temperatures as high as 80°C . or 176°F . and perhaps even higher.

It may be roughly said that higher plants make organic matter out of water from the soil and carbon dioxide from the air, and lower organisms break down again, destroy, what the macroflora has built up. The difference between what higher plants build up and lower organisms break down constitutes that complex entity which is roughly termed "humus."

The important question, is: when and where is humus formed and when and where is humus destroyed; in other words, when and where is humus accumulated, when and where is humus absent, destroyed faster than it is being formed?

Humus formation takes place where a luxurious vegetation prevails, hence in forests, at the proper temperature, or, still

better, where abundant sunshine fosters vigorous assimilation by higher plants, *i.e.*, in the hot equatorial lowlands (as well as in the lowlands of higher latitudes, even if the temperature here has become much lower). Also in the more elevated, cooler highlands of such countries like Java, where the sun stands overhead almost all the year round.

While higher plants need much sunshine, much insolation, the lower organisms on and in the soil, for their best development need heat most of all, next to air and water.

Thus, humus is destroyed most rapidly where the temperature is high and is continuously high, *i.e.*, in the lowlands and in the hill lands of the equatorial regions.

So, humus can be maintained only and can accumulate only where the conditions for its formation are more favorable than the conditions for its destruction, in other words, where higher plants thrive better than the lower organisms. This can best be read from the following diagram.

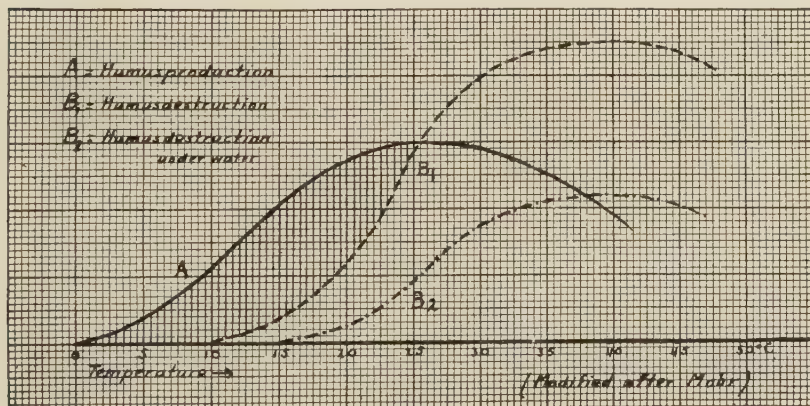


DIAGRAM 1

Thus the conclusion may be drawn, that in humid and hot equatorial regions, with an average temperature of 25° C. and over, humus cannot maintain itself or accumulate in a properly aerated soil.

As the percolating soil water comes in contact with humus, it will dissolve organic substances, and become humus laden

water, brown in color. This, of course, happens only where humus can persist more or less; where humus cannot persist, but is burnt up into carbon dioxide and water, there is no organic matter in the soil-water, but rather carbon dioxide in its stead.

Hence the following conclusions seem justified:

- (1) In humid and hot equatorial regions, where the average temperature is 25° C. or 77° F. and over, the water in the soil does not contain organic matter in solution, provided the soil is well aerated;
- (2) Humus-laden water is found only in the cooler mountain zones of the equatorial regions. In addition, humus-laden water is found also in the lower, hotter zones where the proper supply of air is lacking, *i.e.*, in poorly aerated soils.

This last statement, perhaps, requires some elaboration and explanation.

In soils that are permanently under water, *i.e.*, in marshy and boggy ground, water has largely replaced the air and the soil is lacking in proper aeration. Under such conditions the higher vegetative life may take on another aspect than on the well-aerated soils, yet it is well-known that the luxuriance of the vegetation is but little impaired. Humus formation goes on at much the same rate, so curve *A* in the diagram above needs hardly to be modified. But the micro-flora under such conditions suffers proportionately much more from lack of air, and consequently the total destruction of humus into carbon dioxide and water is much reduced. Hence, if we represent the intensity of humus destruction under these newer conditions by a curve, we would get something like curve *B*₂. It should be noted that this curve crosses curve *A* beyond the limit of importance, if at all. The significance of this should be immediately clear: in water-logged soils humus-accumulation takes place at all temperatures, and the ambient water is humus-laden, brown in color, much the same as such boggy water is in our own middle latitudes.

These conditions affect rock-weathering most profoundly

when it is considered that silica, one of the most abundant constituents of rocks and soils, is relatively most soluble in pure rain-water; the presence in solution of salts, of carbon dioxide or of humus decreases its solubility.

Kaolin, the basis of all that is called clay, is likewise more soluble in pure water than in water containing salts or carbon dioxide or organic matter.

However, iron-oxide and aluminum oxide, other important constituents of soils and rocks, are less soluble in pure rain-water and salt solutions, but are rather easily soluble in humus-laden water.

So it is apparent that if leaching takes place by water free from organic matter, then free silica and even kaolin will be removed in the long run, but iron-oxide and aluminum oxide tend to persist, while leaching by humus-laden water ends up in products that are rich in silica, but poor in iron-oxide and aluminum oxide.

Thus the main types of weathering and soil formation in Java may be summarized as follows:

DIAGRAM 2

		P > E	Alternate Wet and Dry Seasons		P < E
Direction of movement of water in the soil. >		↓ ↓ ↓ ↓	↓ - ↓ - ↓ -	↓ ↑ ↓ ↑	↑ ↑ ↑ ↑
Weathering above ground-water level, i.e. under aerobic conditions	Temperature high low	(1) yellow red (3) white	(2) red —	(4) black —	(5) gray —
Weathering under water, i.e. with lack of air	Temperature high	(6) gray-white	—	(7) black	—

Type 1: temperature high; precipitation always greater than evaporation; soil material loose and pervious, above ground-water level, well aerated—constant downward

leaching by warm rainwater with no organic matter in solution.

It is being recognized more and more that everywhere on the earth this type of weathering will result into end-products which are remarkably uniform, whatever parent-rocks may have furnished the material. Those end-products consist of little else but iron oxide and aluminum oxide, but when the original rock contained quartz and other similarly resistant minerals, then, of course, we would find these little altered as admixtures.

These products of weathering have generally been called "laterite." But as this term "laterite" has been derived from the color, viz. from the color of red brick, which it resembles, and does not convey any knowledge about its mode of formation, and since the same word has given rise to so many misinterpretations and so much misuse, it is desirable to replace it by a more suitable name. Mohr has proposed the term "lixivium" meaning "what has been leached out," to supplant the term "laterite." Under these conditions of weathering iron oxide is accumulated as yellow to brown iron hydroxide, which imparts a yellow to brownish color to the whole mass, hence giving rise to yellow or brown lixivium. In time the hydroxide may naturally become dehydrated and the soil becomes a red lixivium.

Type 2: temperature high; rainy season alternating with more or less dry season; soil material very pervious, above the groundwater level, well aerated; intermittent leaching and enrichment by warm rainwater without organic substances in solution.

This type of weathering again results into a lixivium, poor in silica, rich in iron oxide, which is dehydrated during the dry season, and does not become hydrated again during the wet season. Hence a dominantly red soil, a red lixivium, formerly called a red laterite also, but in reality quite different from the preceding red laterite.

Type 3: temperature low; rainfall always greater than evaporation; constant leaching by cool water, containing more or less humus.

This type of weathering, resulting in a "podsol," such as is most typically exhibited in Canada, Northern Michigan, and Northern Europe, is hardly found in the high mountain and plateau regions of Java. Instead, intermediate stages between type 1 and type 3 are met with. Higher up on the mountain slopes the amount of humus increases, and the percolating soil-water becomes increasingly richer in dissolved organic matter. Under such conditions iron will be removed, whereas silica will persist and increase proportionately. The result is a light colored soil, almost white, resting under a layer of black humus. This light colored soil then is a white "lixivium" and is so called.

Type 4: temperature high; rainy seasons alternating with dry seasons; soil material moderately pervious, but with good capillarity; alternate leaching by warm water with little humus, and enrichment by evaporation of ascending groundwater containing dissolved salts and more or less humus.

In this type of weathering the downward percolating water during the rainy season carries large quantities of carbon dioxide resulting from the destruction of organic matter in the hot season. This water, when drawn upward during the dry season, now contains in solution calcium bicarbonate, besides sodium, potassium, magnesium and iron carbonates. Upon evaporation of the solvent these substances accumulate on or near the surface, where they react with the organic matter, imparting a black color to the soil. Hence a black soil, but not the same shade as the black humus soil of the cooler climates, instead a bluish black to grayish black, as distinct from the brownish black or dark brown of pure humus soils.

Another characteristic feature of these soils is the presence of concretions of lime and of hydrated iron oxide. They are formed at a depth down to which the soil cracks during the dry season, hence down to which aeration takes place.

In the hill zone, higher up than the hot lowlands, the temperature is somewhat lower, and the lack of rainfall during the dry season is less pronounced. Here transitional stages be-

tween 4 and 3 are found, as indicated by the gradual change in color from grayish black and bluish black into brownish black and dark brown.

Type 5: temperature high; precipitation always less than evaporation; alternate wetting and drying out; downward movement of rainwater for a short distance or in occasional cracks, followed by upward movement of salt-bearing water; enrichment by evaporation at the surface (alkali soils).

Such a constantly dry climate, resulting in desert conditions, fortunately does not occur in Java; it may perhaps be found farther eastward, on the adjoining islands of the Malay Archipelago, or in Australia, but so far only small indications of the formation of surface crusts of lime carbonate, gypsum, and rarely other compounds have been found in Java, showing transitional stages between 5 and 4.

Type 6: temperature high; precipitation constantly higher than evaporation; soil permanently under water, continued leaching under water and by humus-laden, warm water.

This type of weathering which may be called subhydric or subaquatic or under-water weathering, results in a rapid and intensive leaching-out process, producing light gray soil, the "Glei" soils of the Russians, which may, at times, have a tinge of darker gray or bluish gray; they contain little else but kaolin and silica and perhaps ferrous sulphides.

The vegetation of such soils, constantly under water, will thrive mostly on whatever nutrients are brought in from elsewhere by the inflowing waters.

Type 7: temperature high; climate with wet and dry seasons; leaching by humous water during the wet season; concentration and enrichment by ascended alkaline water containing organic matter and salts during the dry season.

In this type of weathering which is found in alternately wet and dry swamps, a black soil is formed, less alkaline than (4)

or (3), less leached out than (6) but with more organic matter of the same quality as described from (4). Iron oxide is here characteristically found in concretions again.

CHAPTER III

THE PROBLEM STATED. FIELD AND LABORATORY METHODS

THE essentials in the foregoing discussion may be once more brought out before our particular problem is stated. Mohr has given a reasonable explanation for the reason

(1) why in the tropical lowlands, with abundant rainfall, any kind of rock that weathers under conditions of a proper supply of air and water should eventually become a laterite or a bauxite, both of which being composed of little else but iron and aluminum oxides or hydroxides, usually red in color;

(2) why in the tropical lowlands, with alternate wet and dry seasons, the typical black rice-soils should be developed;

(3) why in the tropical high-mountain zones, with abundant rainfall and middle latitude temperatures, a type of weathering and soil-formation should be found which corresponds to that of the middle latitudes and perhaps even to that of high latitudes, *i.e.*, the type of weathering which is now referred to as "podsolization" and eventually ends up in the formation of a "podsol."

The process of laterization in tropical lowlands has been the subject of countless investigations by scientists of almost every nation since 1807, at which time Francis Buchanan (-Hamilton) gave the name "laterite" to a remarkable, ferruginous residual rock which he had met with on his travels through Southern India.¹¹

Our knowledge of the subject has recently been ably summarized and clarified in the works of Lacroix, Harrassowitz and Fox¹² so that it was not considered expedient nor necessary at this stage to add to the voluminous literature on the problem.

The question of tropical black soils has also received a great deal of attention particularly from the side of resident

British investigators in India and South Africa, and will not be treated at this time.

The problem of podsolization in the tropics, however, has not been studied, so far as the author could determine, except by Mohr. But even he has not systematically set out to study characteristic profiles at definite elevations, nor has he substantiated his theories by the publication of the results of laboratory studies.

Other investigators in the tropics, whether resident or transient, have not yet given the matter any attention, so far as the writer could determine. For these reasons and because of its importance as a test case for modern conceptions on the climatic control of weathering and of major soil characteristics, it was considered worth while to independently investigate the problem in the field and in the laboratory.

This paper, being the result of such investigations, can be regarded as the first attempt at a systematic orientation into the problem of weathering and soil-formation in equatorial high altitudes, specifically on islands of the Oriental tropics.

The Problem Stated

The object of this study is to ascertain whether podsoles are found, respectively whether podsolization takes place in high altitudes in the tropics.

Podsol is the typical soil of large areas in the Northern hemisphere where the climate is humid and cold, yet not too cold for the development of a luxuriant vegetation, mostly of the forest-type, so that plenty of organic matter or humus can be accumulated. The characteristic profile of a podsol shows a dark humous layer of variable thickness on the top, or in the A_1 -horizon so-called. Below it lies an ash-gray layer—the A_2 -horizon—which owes its light color to the removal of coloring matter, such as dark-colored mineral constituents, but mainly the hydrated iron oxides, under the influence of humus-laden percolating waters. A residue of light-colored resistant minerals is left, consisting principally of silica or quartz and muscovite and hydrated aluminum oxides, etc. The iron

oxide migrates downward, enriching the iron content of lower *B*-horizons, and may, under certain conditions, to be discussed later, be precipitated to form a "hardpan," or a layer of so-called "bog iron ore."

In case this final stage of podsolization has not been reached, the soil is spoken of as a podsolized soil. It will then show varying degrees of "lightness" of color of the A_2 -horizon and increasing iron content from the top of the *B*-horizon downward.

It is evident that the development of a podsol, or podsolization in general, is favored by

- (1) a loose and pervious, fragmental parent material;
- (2) an abundance of precipitation all the year around;
- (3) an even and low temperature all the year around;
- (4) a luxuriant primeval forest vegetation.

These conditions are admirably found on many islands of the Oriental tropics, notably on most of the larger islands of the Malay and Philippine Archipelagoes.

The majority of the high mountains in this part of the earth represent cinder and composite cones of extinct or still active volcanoes. The volcanic eruptions which were and still are of the explosive, Vulcanian or Vesuvian type, have given rise to loose and porous deposits, often of great thickness, on the flanks of the mountains and beyond. These ejectamenta or "efflata"—a new word suggested by Mohr, denoting "what has been blown out"—are the usual buff-colored pyroclastics or tuffs of basic igneous rocks that are characteristic of the great majority of the volcanic tuffs of recent Vulcanian eruptions.

There is one serious drawback, however, to the mountains just spoken of, viz., the fact that old soils have often received and are still receiving fresh volcanic dust as the result of eruptions of nearby or even distant volcanoes.

The case of Krakatoa volcano may simply be recalled in this connection. Consequently a great many of the collected samples proved to be unsuitable for the present investigation and had to be discarded.

Field Methods

Since topographic maps are wanting for many of the mountains to be climbed, the author carried a reliable aneroid barometer for determining elevations. This barometer, made by Richard Frères in Paris (France), was the large precision type with a diameter of 9 cm., compensated for temperature changes and reading from -200 m. to $5,000$ m. with intervals of 20 m. The instrument was compared with the ship's mercury-barometer three times daily for a period of three weeks on the voyage from Marseille to Batavia, and was found to be accurate. It was tested again and found accurate by the Royal Magnetic and Meteorological Observatory at Batavia (Java) and once more, with the same result, at the Manila Observatory in the Philippine Islands.

In equatorial regions, particularly those with a marine type of climate, the variations of barometric pressures during the day and from day to day are regular, besides negligibly small. Consequently the determination of elevations in our fields of operation by means of a reliable aneroid barometer may be considered sufficiently accurate, at least for our purposes.

The soil-observations were made on natural cuts or in test-pits especially dug for the purpose. These pits were about 150 cm. long, 50 cm. wide and at least 100 cm. deep. One wall was made smooth and the observations were made on this wall. These observations included (1) the thickness of each distinguishable horizon; (2) its color; (3) its texture and structure. Furthermore, the reaction of each horizon was determined separately and in place by means of the "Soiltex" method according to Spurway, which expresses the hydrogen-ion concentration sufficiently accurately for all practical purposes.* Soil samples of convenient size were then taken from each horizon separately at definite depths. These samples, duly labeled, were put in cloth bags and dried in the shade at the earliest convenience.

* The "Soiltex" indicator-liquid is an aqueous solution of bromthymol blue (Clark and Lubs); it gives a deep blue color with alkaline, and a varied range of yellow colors with acid solutions.

Laboratory Methods

In the laboratory the samples were passed as air-dry soil through a sieve with round holes of 2 mm. diameter, according to the usual methods in soil-analysis. It was often necessary, in this operation, to rub the soil in a mortar with rubber-tipped pestle in order to break up lumps but not stones and gravel. Macroscopic bits of plant-roots and pieces of charcoal were removed as much as was possible.

The part which passed through the 2 mm. sieve, the "fine earth," was taken as the basis for all subsequent determinations, viz., the mechanical, mineralogical and chemical analyses.

The mechanical analysis was carried out according to the standard methods of the United States Bureau of Soils,¹³ in duplicate sets of five grams of the oven-dried material, and the weights were recorded to the third decimal place. The clay content was computed from the difference in weight between the original sample and the sum of total silt and sand. Difficulties were encountered with samples high in humus-content so that several analyses were repeated and an average computed.

The mineralogical analysis was carried out on the sand-fractions separated by means of the mechanical analysis. The methods of analysis were mainly petrographic-microscopical, aided by separation with acetylene tetrabromide of specific gravity 2.95.

The chemical analyses were carried out partly by the writer himself insofar as the laboratory facilities permitted, but mostly by Drs. B. A. Soule and R. K. McAlpine of the Department of Chemistry, University of Michigan, and by Mr. Earl V. Shannon, of the United States National Museum at Washington, D. C., to all of whom the writer may here express his cordial thanks for their coöperation.

Complete analyses, after fusion with sodium carbonate, were made according to the standard methods for rock-analysis.

The fusion method was resorted to rather than the extraction methods by means of strong hydrochloric acid and

strong sulfuric acid, which are more in favor with agricultural chemists. This was done because the problem was considered a geological rather than an agricultural problem, the soils being regarded as geological phenomena per se rather than as a support for plant-life.

The usual elements called for in a complete rock-analysis were thus determined, except ferrous iron, which could not be determined in the presence of so much organic matter. Because of its importance in our considerations the organic matter or humus was determined additionally in three ways:

- (1) as loss on ignition;
- (2) as alkali-soluble humus—the “*matière noire*” or “black matter” of Grandeau;
- (3) as total carbon.

Ad. 1.—The loss on ignition was determined by the chemists referred to on the basis of the sample as received, *i.e.*, in the air-dry condition, by heating over a Méker burner in a platinum crucible. The author made his determinations on the basis of the soil dried at 100° C. and heated in a porcelain crucible at low red heat over an ordinary Bunsen burner, *i.e.*, the customary way in soil-analysis.

Ad. 2.—The “soluble humus” or “black matter” was determined by the author according to the method used in agricultural-chemical analysis, *i.e.*, solution in 4 per cent. ammonia by weight after decalcification with 1 per cent. HCl and subsequent washing out of the acid.¹⁴ An aliquot amount was then drawn off from the filtered solution, evaporated, weighed, ignited and weighed again. The difference in the last two weights represents the alkali-soluble humus or black matter.

Finally it was considered necessary to determine independently the amount of iron hydroxide adsorbed by the soil particles, because of its great importance in the consideration of the migration of iron oxides in the soil. This absorbed iron hydroxide is referred to as colloidal Fe_2O_3 in the tabulation of the analytical results.

Its importance is derived from the fact that, in a recent

physical-chemical study of certain French soils, Demolon has shown that up to 88 per cent. of the total iron oxides ("limonites") in a soil may be so adsorbed on the surface of the soil-particles.¹⁵ He has also found a "rapid" method for its determination which has been essentially followed in our determinations. Since the procedure does not appear to have become known in this country, it is considered worth while to describe it here in full (Demolon, *op. cit.*, pp. 48-49). To 2 g. of soil in an Erlenmeyer flask are added 100 cc. of a 2 per cent aqueous solution of oxalic acid. If the mixture effervesces, which happens when the soil contains more than 0.40 per cent. of alkali-earth carbonates, more powdered oxalic acid is added to correspond with the decomposition by the carbonates. Let the mixture stand for 48 hours, then add 10 cc. of an ammoniacal citrate solution, shake and let digest for 15 minutes. (This ammoniacal citrate solution is prepared by dissolving 400 g. citric acid in concentrated ammonia of 22° to make up 1 liter.)

The mixture is then brought to a standard volume ("on gauge") and filtered; one half is drawn off (representing 1 g. of material) and transferred to a precipitating flask. Add a few drops of H_2O_2 and boil. Add gradually 20 per cent. KOH and heat until the ammonia is eliminated with the complete separation of the iron in floccules. Filter, wash and redissolve the precipitate in a boiling solution containing 12 per cent. by volume of strong HCl of 22° Bé. Titrate with standardized sodium thiosulfate solution containing 5 g. per liter in the presence of sodium salicylate and a small quantity of copper sulfate which acts as a catalyzer, according to Landolt (*Bull. Ass. Chim. d. Sucrierie*, 1921, 8, 477).

The soil sample must not have been heated or ignited because "limonite" that has been heated to as low as 200° C. is no longer soluble in oxalic acid. Previous decalcification with dilute HCl—1 per cent. is ordinarily used—should also be avoided, for it always results in dissolving a small quantity of iron.

CHAPTER IV

RESULTS OF FIELD AND LABORATORY WORK

THE field observations bore out, in general, the findings of Mohr as they have been discussed in Chapter II. This was true for the Dutch East Indies as well as for the Philippine Islands.

In the lowlands the soils were found to be dominantly red in color with no evidence of organic matter in them. They were sticky and stiff when wet, hard and cracked when dry, thus showing the characteristics of clay without humus. The rice and marsh soils (Mohr's type No. 7), next to the red soils the most important so far as their extent is concerned, were generally found to be black or grayish-black in color, equally stiff and sticky when wet and equally prone to become hard and to develop cracks when dry. However, black soils rich in humus were also noticed in the lowlands where they developed under well-aërated conditions, even in sands. But they were found only under a grassy vegetation, viz., under the kind of tall and coarse grass which is called "alang-alang" or "lalang" in the Dutch East Indies and "cogon" in the Philippine Islands (*Imperata arundinacea*).

This is a problem, the explanation of which requires more study and does not concern us here. A similarity may be suggested between the processes of organic matter preservation on tropical grassy plains and on the prairies of the middle latitudes.

As one went up the mountain slopes, humus began to appear under forest cover and increased visibly as one went higher and higher. But the dominant color of the soil remained red, though not the bright brick-red of the lowlands, but rather a brownish-red, over chocolate brown and chestnut brown to dark blackish brown, due to the admixture of increasing amounts of humus—except in the case of fresh to fairly fresh volcanic tuff soils. Their buff color naturally persisted the longest on the slopes of the active volcanoes as it did often also on the slopes of an extinct volcano in close

proximity to an active one. These phenomena were particularly well exhibited on the slopes of the twin volcanoes Merapi (active) and Merbabou (extinct) in Central Java, whose individual peaks are about 10 km. apart.

Soil textures and structures also changed as one went up the mountain slopes. The stiff impervious clay-soils of the lowlands gave way to a loose, friable and porous sand, often remarkably uniform to great depths—except in the case of young volcanic efflata soils. These became rapidly coarser the more closely they were deposited near the volcanic center of eruption and often showed layers of greatly varying texture over a small range of depths.

Those facts spoilt the use, for the present purpose, of all the samples collected on the active volcanoes and of many of those from extinct or dormant volcanoes as well. They represent immature stages of soil-development, they are “Skellett-böden” or skeleton-soils, according to Ramann, constituting one of the many forms in which “local” (Ramann) or “endodynamomorphic” (Glinka) soils may appear; they clearly are not “climatic” (Ramann) or “ektodynamomorphic” (Glinka) or “zonal” (Dokuchaiev, Sibirtsev) soils and hence will not be mentioned in the following discussions.

In all, a dozen mountains were climbed in order to collect the field observations and the representative soil samples. Eight are located in Java and four in the Philippine Islands as follows:

TABLE 3

Name	Location	Kind	Elevation
Mt. Andjasmoro..	East Java	Extinct volcano	2,342 m. (7,760 ft.)
Mt. Kelout.....	Central Java	Active “	1,731 m. (5,680 ft.)
Mt. Lawou.....	“ “	Extinct “	3,265 m. (10,700 ft.)
Mt. Merbabou...	“ “	“ “	3,145 m. (10,300 ft.)
Mt. Merapi.....	“ “	Active “	2,910 m. (9,550 ft.)
Diëng Plateau....	“ “	Fumarolic region	2,100 m. (6,890 ft.)
Mt. Malabar....	West Java	Extinct volcano	2,343 m. (7,680 ft.)
Mt. Gedé.....	“ “	Active “	2,962 m. (9,710 ft.)
Mt. Canlaon....	Negros, P. I.	“ “	2,438 m. (8,000 ft.)
Mt. Banahao....	Luzon, P. I.	Extinct “	2,188 m. (7,180 ft.)
Mt. Maquiling...	“ “ “	“ “	1,144 m. (3,750 ft.)
Mt. Santo Thomas	“ “ “	Structural mountain	2,258 m. (7,400 ft.)

Nowhere did the field observations show the presence of a typical podsol such as is familiar to the author from Northern Michigan and Southern Canada (Province of Ontario).

Mohr (*op. cit.*, 10, pp. 102-103) considers certain white soils which he found on the Diëng Plateau (2,100 m.) as being podsoles although he calls them, by a self-coined name "*altopallescium*" (meaning: what has been bleached due to the elevation, *i.e.*, the cooler climate prevailing at this high altitude). The author, however, could establish in the field that those soils are not podsoles, but have been bleached by pneumatolytic processes.

In the first place, this whole plateau abounds with features that are characteristic of the waning stages of volcanic activity, such as fumaroles, solfatara, mofettas, etc.

In the second place, the white soils were found only in distinctly localized areas of small extent, here and there, but by no means regularly under the rather thick covering of muck or peat which had accumulated in the numerous swamps, nor under the humus-cover on dry land.

Thirdly, the author was enabled to see fresh exposures in cross-section for thicknesses of over 30 m., which were caused by landslides resulting from a severe earthquake of the year before. These cross-sections showed the white deposits to have a convex upward form, sharply defined from the surrounding and overlying dark-colored soil. This form is wholly consistent with the view that pneumatolytic gases, be they laden with sulfur dioxide or carbon dioxide, have diffused from an orifice below, upward through the mass of soil material, and have caused the alteration and bleaching of the soil minerals. The process is thus analogous with one of the three ways by which kaolin is known to have been formed.¹⁶

In the fourth place, the author found many examples of such bleaching action of volcanic exhalations going on at the present time around active fumaroles. This fact is too well known among geologists to need further elaboration.

In the fifth place, nowhere did one find accumulations into layers or concretions or "hardpans" of the iron oxide,

supposedly washed downward by the percolating humus-laden waters—a characteristic feature of most true podsol profiles.¹⁷

Finally, it would require a great strain on one's imagination to conceive of podsoles having been formed to a thickness of 30 m. and perhaps more, considering the fact that the soil-forming material must have been only recently deposited (geologically speaking) in this region of waning volcanic activity. Thus there is no doubt in the writer's mind that Mohr's so-called "altopallescium" is not podsol as he wrongly believes.

While the true podsol was nowhere encountered in the field, yet evidence was not wanting that the process of podsolization does take place in the tropical high altitudes under consideration. Indications to that effect were found in the generally lighter coloration of subsoils under humus, such as will presently be described.

Subsequent laboratory investigations confirmed the field observations, and may now be presented and discussed.

The laboratory investigations were carried out on whole profiles, up to the depth of one meter, of carefully selected samples. Injustice would have been done to the theory if every mountain soil had been taken into consideration without regard to the elevation or irrespective of whether the soil-material was fresh or not. Hence all profiles below 2,000 m. were eliminated, and so were the ones that showed too recent an origin. This required preliminary mechanical analyses and examination of many samples that were subsequently culled out. In this way only three of the forty odd profiles passed the elimination tests, as follows:

Mt. Lawou, Central Java, W. slope at 2,800 m.

Mt. Malabar, West Java, S.S.W. slope at 2,200 m.

Mt. Banahao, Luzon, S.W. slope at 2,100 m.

Soil from Mt. Lawou, Java

This soil was collected November 16, 1925, on the west slope of Mt. Lawou in Central Java at an elevation of 2,800 m.

Climatic data are not available for this elevation, nor for any nearby station, so that they can only be surmised from the general considerations in Chapter II.

On November 15, 1925, the air-temperature at an elevation of 2,040 m. at 10 A.M., sun shining, in mountain forest, was 22° C., whereas the soil-temperature, 5 cm. deep, was 16° C. At 2,720 m., 2 P.M., the air-temperature, with sun obscured, was 18° C. and at 3,020 m., 5 A.M., the thermometer registered 5° C.

The primeval forest trees were dripping wet until about 10 A.M., and the undergrowth, particularly the mosses, was wet all the time. The clouds began to gather around noon and drizzling rain fell around 3 P.M., lasting all through the night until about 6 A.M. Yet, the nearby lowlands, at the time, were experiencing an exceptionally protracted dry season. These chance observations agree fairly well with the general considerations in Chapter II and enable us to assume an average temperature of 11° C., at the stated elevation, with abundant rainfall all the year around.

The soil under primeval mountain forest at an elevation of 2,800 m. showed a typical profile as follows:

Horizon *A* from 0–30 cm.: a moist, loose, fine sandy, dark-brown humous layer without pebbles or stones or concretions; $pH = 5.0$

Horizon *B* from 30–100 cm.: a moist, loose, fine sandy, yellowish-gray layer; in exposed places becomes dusty, rather compact, uniform in texture, and pinkish in color; $pH = 5.0$

Samples of both horizons were taken and analyzed separately under the serial numbers 106 and 107.

In the air-dry condition the topsoil has a dark gray color and the subsoil a light buff color with a yellow cast.

The *mechanical analyses* are tabulated in Table 4. They show the *B*-horizon to be somewhat finer in texture than the *A*-horizon. The first one is a loam and the second a sandy loam according to the classification of the United States Bureau of Soils.

TABLE 4
MECHANICAL ANALYSES

	Java: Mt. Lawou W-slope 2,800 m.		Java: Mt. Malabar SSW-slope 2,200 m.			Luzon: Mt. Banahao SW-slope 2,100 m.		
Serial number.....	106 <i>A</i>	107 <i>B</i>	101 <i>A</i> ₁	102 <i>A</i> ₂	103 <i>B</i>	121 <i>A</i>	122 <i>B</i> ₁	123 <i>B</i> ₂
Horizon.....	0-30	50-70	0-15	15-35	50-70	0-20	20-25	25-50
Depth in cm.....	None	None	None	None	None	None	None	None
Coarse gravel > 2 mm.....	58.16	48.06	84.75	84.23	85.88	82.44	86.84	84.06
Total sand 2-0.05 mm.....	31.30	43.53	6.30	7.22	8.20	10.70	9.21	12.18
Total silt 0.05-0.005 mm.....	10.54	8.40	8.95	8.55	5.92	6.86	3.95	3.76
Total clay < 0.005 mm.....	Sandy loam	Loam	Sand	Sand	Sand	Sand	Sand	Sand
Class name.....								
GRADES								
1. Fine gravel 2-1 mm.....	1.87	1.36	18.22	21.07	16.28	6.69	1.99	3.61
2. Coarse sand 1-0.5 mm.....	13.32	3.93	29.87	23.94	17.92	17.08	14.91	14.11
3. Medium sand 0.5-0.25 mm.....	10.24	6.31	16.81	15.39	13.34	19.22	22.25	18.81
4. Fine sand 0.25-0.10 mm.....	18.51	15.78	14.44	16.59	22.74	27.28	32.18	30.53
5. Very fine sand 0.10-0.05 mm.....	13.90	20.88	5.18	7.56	16.72	11.86	15.75	17.27
6. Silt 0.05-0.005 mm.....	31.30	43.53	6.30	7.22	8.20	10.70	9.21	12.18
7. Clay < 0.005 mm.....	10.54	8.40	8.95	8.55	5.92	6.86	3.95	3.76
Moisture 100°.....	99.68	100.19	99.77	100.32	101.12	99.69	100.24	100.27
Ignition loss.....	4.26	2.82	6.94	7.82	11.55	8.40	11.18	10.95
	26.45	15.32	38.29	32.87	30.67	38.04	30.45	27.23

The *mineralogical analysis* shows all the fractions of the *A*-horizon to be dark in color due to the admixture of organic matter, such as bits of plant-structures, charcoal and charcoal-like carbonaceous matter, all of which occupy the greatest bulk. The fractions of the *B*-horizon are all light gray in color with little carbonaceous matter. The mineral particles in both horizons are angular and look quite fresh. The topsoil contains about 8 per cent. (by weight) of heavy minerals (s.g. > 2.95) and the subsoil about 12 per cent. No difference was found between the constituents of topsoil and sub-soil.

The following mineral constituents were recognized: bits of andesitic pyroclastics and volcanic glass, plagioclase feldspars, quartz, iron-stained translucent chert or flint, augite, hornblende, magnetite and ilmenite and tourmaline.

The *chemical analysis* tabulated in Table 5 shows both samples to have approximately the same composition, little different from that of an andesite, such as has been reported from this volcano by Verbeek and Fennema, viz., a pyroxene-andesite.¹⁸ It should be noted that the amounts of alkali and alkali-earth metals are somewhat lower than in most andesites.¹⁹ Their compounds, however, are among the first to be removed in chemical weathering of any kind. It should therefore not be surprising that under the prevailing conditions of heavy rainfall the year round and a pervious substratum, the percolating meteoric waters should have noticeably decreased the amounts of alkali and alkali-earth metals. Nevertheless, the material is essentially the same as it was when deposited as volcanic tuff. Hence it has not yet become a climatic soil; the light-colored subsoil which, in the field, looked like a podsol-horizon is actually but a tuff-layer, little changed since it was deposited. This particular soil, then, is only a skeleton-soil at best and must for that reason be discarded from our discussion of climatic soil-types.

In passing, a seeming anomaly may be pointed out in the distribution of the alkali and alkali-earth metals. Ordinarily these substances increase downward in a humid soil, but in

this soil the reverse is the case. This fact becomes intelligible when it is considered that Mt. Lawou is located between two active volcanoes of the Vesuvian type, viz., Mt. Merapi, distant by about 100 km. to the west, and Mt. Kelout, about 150 km. to the east. Both of these volcanoes have had frequent eruptions in recent historical times, thereby ejecting large quantities of volcanic tuffs far and wide. Thus the

TABLE 5

Java (Neth. East Indies): Mt. Lawou; W. slope at 2,800 m.

CHEMICAL ANALYSES

Ss means determined by author;

McA means determined by R. K. McAlpine;

Columns I refer to the percentages in the air-dry sample as is;

Columns II refer to the same percentages recalculated on the basis of the mineral part = 100.

	Serial No. 106 Horizon A 0-30 cm.	Serial No. 107 Horizon B 50-75 cm.
Ss <i>pH</i>	2.0	5.0
" Moisture 100°.....	4.26	2.83
" Ignition loss.....	26.45	15.32
" "Black matter" (alkali-soluble humus).	10.50	7.17

TOTAL ANALYSIS

	I	II	I	II
McA Ignition loss.	27.65	—	16.69	—
" SiO ₂	43.59	60.25	52.02	62.44
" TiO ₂	0.68	0.94	0.83	1.00
" Al ₂ O ₃	13.27	18.34	14.41	17.30
" Fe ₂ O ₃	6.92	9.56	7.69	9.23
" MnO.....	0.40	0.55	0.40	0.48
" CaO.....	2.81	3.88	2.13	2.56
" MgO.....	1.37	1.89	1.35	1.62
" Na ₂ O.....	1.90	2.62	2.12	2.54
" K ₂ O.....	1.46	2.02	2.22	2.66
" P ₂ O ₅	0.21	0.29	0.20	0.24
" SO ₃	0.52	0.72	0.62	0.75
	100.78		100.58	
" Total carbon.....	11.19		6.82	
" Organic matter (C × 1.724).....	20.52		11.76	
" Fe ₂ O ₃ colloidal.....	3.19	4.41	4.09	4.91
<i>id. id. (in total Fe₂O₃)</i>		45.05		53.18

Kelout eruption of 1901 contributed a dust-layer, at least 2 cm. thick, to the nearby city of Souracarta, which is located some 40 km. farther to the west from Mt. Lawou. A still greater eruption of the same volcano took place as recently as the year 1919 and covered almost the whole island of Java with a more or less thick layer of fresh volcanic dust of the alkali-lime series of rocks. Thus the slopes of Mt. Lawou have received fresh soil-forming material on various occasions in the near past, which explains the uncommon distribution of the alkali and alkali-earth metals in the soil column.

This matter is emphasized here because the same phenomena, due to similar causes, occur also in the two other soils to be discussed presently.

J. Th. White has recently published a generalized geological map of Java on which the distribution of such deposits has been indicated as to source, thickness and extent.²⁰

Soil from Mt. Malabar, Java

This second soil from Java was collected December 22, 1925, on the S.S.W. slope of Mt. Malabar in West Java at an elevation of 2,200 m.

Temperature and rainfall records are available for a nearby station, some 600 m. lower down on the same slope, viz., for the Government Cinchona Experiment Station at Tjinjirean, 1,585 m. above sea-level.

The mean temperature, measured here over a period of ten years (1905-1915), is 16.7° C. (62° F.).²¹ With a temperature gradient, according to Braak (*op. cit.*, p. 322), of 0.61° C. for a rise of 100 m. in the free atmosphere, the average annual temperature at 2,200 m. may be estimated at about 13° C. (55° F.) The average annual rainfall, as measured for a period of 44 years at the lower Station, is 2,900 mm. (115 inches) and no month has less than three inches of rainfall.²² It may safely be assumed that the average rainfall is appreciably higher at the elevation of 2,200 m. since this altitude is within the zone of cloud gathering. The vegetation was a luxuriant primeval forest, typical of this elevation.

The characteristic soil-profile showed the following sequence of horizons:

Horizon A_1 from 0–15 cm.—a moist, dark-brown humous layer, uniformly sandy in texture, loose, friable and porous, without stones or gravel, $pH = 5.5$

Horizon A_2 from 15–35 cm.—a moist, dark yellowish-brown layer of same texture and structure as A_1 , $pH = 5.8$

Horizon B from 35–100 cm.—a moist, light yellowish-brown layer of same texture and structure as A_1 and A_2 , $pH = 5.3$

Samples of each horizon were collected and analyzed under the serial numbers 101, 102 and 103 respectively.

In the air-dry condition, A_1 (101) has a dark chestnut-brown color, A_2 (102) a lighter shade of chestnut brown while B (103) has a distinctly reddish tint, which may be likened to chocolate brown.

The *mechanical analyses* as reported in Table 4 show all three horizons to be in the textural class of sands. There is little difference between A_1 and A_2 , while B contains somewhat more of grade 4 (fine sand). The small amount of clay, < 0.005 mm., should be emphasized as well as the fact that it decreased downward, another anomalous fact to be spoken of later.

The *mineralogical analyses* show 101 to have about 7 per cent. (by weight) of heavy constituents of s.g. > 2.95 , 102 about 2 per cent. and 103 about 1 per cent. The individual minerals are dominantly angular in shape, except for the secondary chert and flint and the shot-like concretions of iron oxides to be spoken of presently. The same minerals as present in the Lawou soil were found here, viz., plagioclase feldspars, some quartz, translucent chert or flint, hornblende, augite, hypersthene, magnetite, ilmenite (?) and pieces of tuff, more or less coated with iron oxide. Debris of plant structures and charcoal-like substances occupy the greatest bulk in 101 and 102, imparting a dark gray-black color to the A_1 horizon. This color is somewhat modified in A_2 by the presence, in about equal bulk as the organic matter, of opaque,

amorphous, shot-like, chocolate-brown concretionary grains of various sizes, which are the dominant constituents in the *B*-horizon. In the dry state the material is brittle, can easily be crushed, is homogeneous and has a specific gravity of 2.56. It represents undoubtedly a gel-mineral of iron hydroxide, more porous than limonite and hence of lower specific gravity

TABLE 6

Java (Neth. East Indies): Mt. Malabar; S.S.W. slope at 2,200 m.

CHEMICAL ANALYSES

Ss means determined by author;

So means determined by B. A. Soule;

Columns I refer to the percentages in the air-dry sample as is;

Columns II refer to the same percentages recalculated on the basis of the mineral part = 100.

	Serial No. 101 Horizon A ₁ 0-15 cm.	Serial No. 102 Horizon A ₂ 15-35 cm.	Serial No. 103 Horizon B 50-70 cm.
Ss <i>pH</i>	5.5	5.8	5.3
" Moisture 100°.....	6.30	7.22	8.20
" Ignition loss.....	38.29	32.87	30.67
" "Black matter" (alkali-soluble humus).....	13.15	13.00	7.45

TOTAL ANALYSIS

	I	II	I	II	I	II
So Ignition loss.....	43.95	—	34.00	—	40.80	—
" SiO ₂	26.91	48.01	30.60	46.37	19.90	33.61
" TiO ₂	0.90	1.61	0.98	1.49	1.26	2.13
" Al ₂ O ₃	12.23	21.82	15.50	23.49	21.98	37.13
" Fe ₂ O ₃	7.07	12.61	10.75	16.26	11.80	19.93
" MnO.....	0.12	0.21	0.15	0.23	0.14	0.24
" CaO.....	4.46	7.96	3.59	5.44	0.82	1.39
" MgO.....	2.10	3.75	2.02	3.06	1.45	2.45
" Na ₂ O.....	1.11	1.98	1.01	1.53	Tr.	—
" K ₂ O.....	0.50	0.89	0.50	0.76	0.18	0.30
" P ₂ O ₅	0.25	0.45	0.34	0.52	0.29	0.49
" SO ₃	0.45	0.80	0.38	0.58	0.98	1.66
	100.05		99.80		99.60	
" Total carbon.....	16.68		13.26		7.81	
" Organic matter (C × 1.724)...	28.76		22.81		13.46	
" Fe ₂ O ₃ (colloidal).....	1.42		Tr.		7.04	11.89
<i>id.</i> <i>id.</i> (in total Fe ₂ O ₃)		2.53		—		59.66
		20.08		—		

because of its granular structure. These characteristic grains were not present in the original soil under natural conditions; they could not have been overlooked had they been present.

The *chemical analyses* as tabulated in Table 6 will be discussed with the next soil, viz.,

Soil from Mt. Banahao, Luzon

Only one soil from the Philippines was found suitable for our purpose. It was collected February 15, 1926, on the S.W. slope of Mt. Banahao, Luzon (about 14° N.), at an elevation of 2,100 m.

Climatic records are available for one of its tops on the N.E. side at an altitude of about 2,100 m. The records were collected by Dr. W. H. Brown of the Philippine Bureau of Science for the period of one year, from November 1915 to November 1916, and show a mean temperature of 14.6° C. (58° F.) and a mean annual rainfall of 7,468 mm. (294 inches).²³ Brown remarks as follows on the monthly distribution of rainfall: "the rainfall on the northern and northeastern slopes of Mt. Banahao is distributed throughout all the months of the year, and there are no distinct wet and dry seasons." Practically the same conditions may be assumed to prevail in our locality.

Mt. Banahao, like Mt. Malabar (and Mt. Lawou) in Java, is an extinct strato-volcano of the Vesuvian type, although it is true that the writer found more basaltic lava at its base than he has met with in Java. Only one eruption of the year 1730 is known to have taken place in historical times.²⁴ But like the Javanese volcanoes, Mt. Banahao has received andesitic pyroclastics from nearby volcanoes, notably from Mt. Taal, located some 45 km. to the west. During its explosive eruption of January 27, 1911, Mt. Taal, according to Pratt, covered an area of 2,000 square km. with ash, which was deposited to a distance of 52 km. from the crater, that is, in a radius which includes Mt. Banahao. This is only one of a number of eruptions which Taal volcano has had all during recent and remote historical times.

The soil-forming material on Mt. Banahao shows the same origin from andesitic pyroclastics as does the parent-material of the Javanese soils, mentioned above.

The typical soil profile at an elevation of 2,100 m. under tropical mountain forest was as follows:

Horizon *A* from 0–20 cm.—a moist grayish-black humous layer, uniformly sandy in texture, loose and friable, $pH = 5.8$

Horizon *B*₁ from 20–25 cm.—a thin layer, peculiarly turkish red or orange red in color; sandy texture, friable, porous, without concretions, stones or gravel; $pH = 4.9$

Horizon *B*₂ from 25–100 cm.—a moist yellowish-brown sand, friable, with decomposed parts of the original pyroclastics up to pebble size, thoroughly weathered and easily crumbled between the fingers; $pH = 6.1$

Samples were taken and analyzed of each horizon separately under the serial numbers 121, 122, 123 respectively.

In the air-dry condition, horizon *A* (121) shows a dark chestnut-brown color, horizon *B*₁ a lighter chestnut brown with brick-red specks and horizon *B*₂ a somewhat lighter shade than *B*₁ with the same orange-yellow or brick-red specks. Numbers 122 and 123 particularly had to be broken up in a mortar with rubber-tipped pestle since the samples had become hard and lumpy. Practically all of the material passed through the 2 mm. sieve.

The results of the *mechanical analyses* are tabulated in Table 4. The whole soil is a sand according to the classification of the United States Bureau of Soils. Numbers 122 and 123 resemble one another more closely than they do number 121, a fact that is borne out by the chemical analysis. The decrease downward of clay particles < 0.005 mm. may again be emphasized in this case as representing quite the opposite from the conditions in an ordinary soil which usually increases in clay-content with depth.

The *mineralogical analyses* show about 4 per cent. (by weight) of the heavy constituents in the topsoil and 8 per cent. in the subsoil. No individual minerals other than those men-

tioned in the Malabar soil were found here, thus suggesting a parent-material of about the same composition in both cases. Organic matter is as dominant in number 121 as it is in 101, imparting a dark grayish-black color to all grades. While organic matter is still present in number 122 (as also in 123), yet its color is overshadowed by orange-red concretions of all sizes from 2 mm. down, the individual grains having a less regular shape than those of numbers 102 and 103, described previously. They are brittle in the dry state, and are homogeneous in composition and not merely coatings on mineral particles. They doubtless represent a similar gel-mineral of iron oxide, even if the color is somewhat different. It has namely been shown by colloid-chemists that ferric hydroxide gels can be made to exhibit colors ranging from yellow to red by merely increasing the size of the colloidal micellæ. In this way red forms have been produced from finely divided yellow particles by agglomeration.²⁵

Discussion of the Chemical Analyses

It was soon realized in the course of the laboratory investigations that neither the mechanical nor the mineralogical analysis, nor both together, could lead to quantitative results which would enable one to draw conclusions concerning the relation between climate and the particular form of weathering and soil-formation encountered in tropical high altitudes.

The chemical analysis was therefore resorted to for possible clues.

Although a great many analyses of Javanese and Philippine soils are known (see for instance *op. cit.*, 20, and bibliography number 25), yet they are of little or no value for our purposes. They were made for agricultural purposes according to the methods of partial analysis in use in agricultural chemistry, so that they often contain only determinations of the agriculturally important elements, K, P, N, Ca, besides organic matter. Furthermore, no elevations are mentioned because no interest had been shown as yet for the soils of the high-mountain regions which only concern us here.

It was therefore necessary to have complete analyses specially made, the number of which being largely determined by financial carrying power. This was also the most cogent reason for limiting the present study to the particular phase of weathering in high altitudes.

The results of the chemical analyses are tabulated in Tables 6 and 7.

TABLE 7

Luzon (Philippine Islands): Mt. Banahao; S.W. slope at 2,100 m.

CHEMICAL ANALYSES

Ss means determined by author;

Sh means determined by Earl V. Shannon;

Columns I refer to the percentages in the air-dry material as is;

Columns II refer to the same percentages recalculated on the basis of mineral part = 100.

	Serial No. 121 Horizon A 0-15 cm.	Serial No. 122 Horizon B ₁ 20-25 cm.	Serial No. 123 Horizon B ₂ 25-50 cm.
Ss pH.....	5.8	4.9	6.1
" Moisture 100°.....	8.40	11.18	10.95
" Ignition loss.....	38.04	30.45	27.23
" "Black matter" (alkali-soluble humus).....	13.91	n.d.	6.97

TOTAL ANALYSIS

	I	II	I	II	I	II
Sh H ₂ O - 110°	8.76	—	11.60	—	11.60	—
" H ₂ O 110°.....	10.32	—	12.20	—	11.97	—
" Ignition loss (in excess of H ₂ O).....	29.26	—	16.93	—	14.61	—
" SiO ₂	21.26	41.15	22.37	37.74	22.08	35.72
" TiO ₂	0.70	1.39	0.64	1.08	0.87	1.41
" Al ₂ O ₃	15.35	29.71	21.82	36.83	22.62	36.59
" Fe ₂ O ₃	5.74	11.11	8.79	14.83	9.83	15.90
" MnO.....	0.08	0.15	0.06	0.10	0.06	0.10
" CaO.....	3.48	6.74	2.47	4.17	2.52	4.08
" MgO.....	1.76	3.41	1.96	3.31	1.93	3.12
" Na ₂ O.....	1.73	3.36	0.52	0.87	1.26	2.04
" K ₂ O.....	1.39	2.69	0.36	0.61	0.36	0.58
" P ₂ O ₅	0.33	0.64	0.25	0.42	0.22	0.16
" S.....	0.17	0.33	0.18	0.30	0.10	0.26
	100.33		100.15		100.09	
" Organic matter (CO ₂ × 0.471 × 2)...	30.50		17.49		14.88	
" Fe ₂ O ₃ (colloidal).....	4.23	8.19	6.95	11.73	8.90	14.40
id. id. (in total Fe ₂ O ₃).....		79.69		79.07		90.54

Their examination reveals the fact that soils 101 and 102 are practically the same and so are soils 122 and 123. It is therefore considered justifiable to confine the discussion mainly to the different pairs 101 and 103, respectively 121 and 123, as representing the *A* and *B* horizons of the Malabar and Banahao soils. Numbers 102 and 122 will only occasionally be referred to.

The minor constituents, such as MnO , TiO_2 , P_2O_5 and S , do not materially affect our problem, so that they will likewise be omitted from the discussion; their determination was mainly carried out for completeness' sake.

The following points require our greatest attention as bearing directly on the problem under investigation:

- (1) the soil reaction as expressed in the approximate hydrogen-ion concentration determined in the field;
- (2) the distribution of organic matter, both total and soluble (black matter);
- (3) the distribution over the soil profile of the alkali and alkali-earth metals;
- (4) the distribution over the soil profile and the migration of SiO_2 ;
- (5) the distribution over the soil profile and the migration of Al_2O_3 ;
- (6) the distribution over the soil profile and the migration of Fe_2O_3 .

An examination of the analytical results, as recalculated on the basis of the mineral part = 100, reveals that:

- Ad. 1—both soils are acid over the entire profile, medium to strongly acid as regards the intensity of acidity expressed in the hydrogen-ion concentration;
- Ad. 2—the humus content decreases downward in the normal way, but even the lowest horizon contains abundant humus, viz., the kind of acid or “raw” humus such as is found in peat-bogs;
- Ad. 3—the alkalis and alkali earths are richer on top than in lower horizons, an anomalous condition that has previously been pointed out and explained;

- Ad. 4— SiO_2 in both soils increases upward, proportionally more in the Malabar soil than in the Banahao soil;
Ad. 5— Al_2O_3 increases downward, proportionally more in the Malabar than in the Banahao soil;
Ad. 6— Fe_2O_3 increases downward proportionally more in the Malabar than in the Banahao soil.

It has been stated before and may be repeated here, that the process of podsolization results in a (relative) increase of silica in the upper horizon and a decrease of alumina and iron oxides, brought about by the presence of acid humus in the water percolating through the soil-forming material, thereby causing the soil to be bleached. O. Tamm, who has recently made a thorough investigation of the problem, states that no kaolinization, *i.e.*, clay-formation, occurs in this process.²⁸

The opposite of podsolization is laterization, which results in a decrease of silica in the upper horizon and an increase of alumina and iron oxides due to the absence of humus in the percolating water.

Thus the results of the chemical analyses indicate that podsolization rather than laterization takes place in the Malabar and Banahao soils.

The mechanical analyses have previously established the fact that clay is practically absent, which is in accordance with Tamm's findings and points toward the occurrence of podsolization.

Finally, the field evidence has shown that the A_2 horizons are distinctly lighter in color than either the A_1 or the B horizons.

Hence we may reach the conclusion that:

Podsolization does take place in high mountain zones of the Oriental tropics in much the same way as it does in the lowlands of the middle latitudes.

Differences do exist, but these differences are such of degree only and not of fundamental character.

Thus the bleached horizon is often much thicker in the tropical high mountain zones than is ordinarily the case in the middle latitudes. This fact indicates a greater intensity in

the process of podsolization, which is readily accounted for by considering that the rainfall is much greater in the tropical high mountain zone than in the middle latitudes, where podsolization usually occurs. Thus the leaching and bleaching processes are naturally bound to be more intensive.

Nevertheless, it might be argued that a true podsol, which consists of little else but silica, has not been found anywhere. This objection also finds a ready and natural explanation when we consider the genesis of the soil-forming parent-material and its episodic additions of fresh pyroclastics which take place to this day as they have taken place in the near past.

Thus the results of these investigations lend good support, from the Oriental tropics, to the principles upon which is built the modern climatic classification of soils, and the author hopes for a chance to verify these findings in the Occidental tropics.

At this stage it is fitting to inquire into the mechanism of the migration of silica, alumina and iron oxides as these are the main constituents the removal or enrichment of which is characteristic of the process of podsolization.

As for *silica*, it was thought, at one time, that in chemical weathering silica was transported in molecular solution as a silicate. Nowadays the consensus of opinion is that silica migrates mostly as a colloidal solution, as a hydrosol of SiO_2 the electrical charge of which may be negative or positive. According to Taylor²⁸ hydrous silica is positively charged in acid solution. Consequently it is so charged in our acid soils. In this condition it is very unstable and easily precipitated as an irreversible gel by an electrolyte which neutralizes its charge. When so precipitated silica becomes more stable and resistant to solution and subsequent transportation. The chemical analyses show that our soils contain large amounts of alkali and alkali-earth compounds in the upper horizon, which upon weathering give rise to negatively charged electrolytes, viz., the bases such as $\text{Ca}(\text{OH})_2$, $\text{Mg}(\text{OH})_2$, KOH , NaOH . Thus it is easily seen that favorable conditions are present for the silica hydrosol to be precipitated and kept in the upper

horizon by interaction with the liberated bases. Since the base-liberating substances decrease downward, gelation and insolubilization of the silica will also decrease downward, and relatively more silica hydrosol can be removed to still lower depths, thus accounting for the decrease of silica downward.

A confirmation of this view may be found in the fact, noted above, that the silica has proportionally decreased more in the lower horizon of the Malabar soil than of the Banahao soil. This fact can be readily explained by comparing the sums of the alkali and alkali-earth metals in both soils. Such a comparison shows that the Malabar soil has retained less of the base-forming elements than the Banahao soil. The figures are 14.58 per cent. and 4.14 per cent. respectively for the *A*- and *B*-horizons of the Malabar soil, 15.20 per cent. and 10.82 per cent. for the corresponding horizons of the Banahao soil. Thus it is readily seen why the downward migration of silica has taken place more slowly in the Banahao soil than in the Malabar soil.

A study of the migration of *alumina* is capable of correcting an error in the minds of many geologists and petrologists concerning the stability of aluminum in rock-weathering. The general assumption is that in the weathering of rocks aluminum oxide is the most stable component of minerals. For that reason chemical calculations of alterations are based on the assumed immutability of alumina. This assumption was perhaps founded on the fact that aluminum does not form readily soluble and removable compounds, carbonates for instance, such as iron, potassium, calcium, etc., do.

Soil students have known for some time that aluminum oxide, as it occurs in soil-forming mineral matter, is subject to rather ready removal in the presence of organic matter. The chemical analyses of our two soils are illustrative of this fact. Caution should therefore be exercised in the interpretation of chemical analyses of weathered rocks recalculated on the basis of alumina as a fixed standard, unless the conditions of weathering are stated and exclude the possibility of the presence of appreciable quantities of organic matter.

It is now generally agreed that aluminum is transported, or migrates, as a hydrosol of the probable composition $\text{Al}(\text{OH})_3$ or $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ with a positive charge. In inorganic solutions it is easily precipitated by electrolytes of opposite charge, but in humus-laden water the humus acts as a protective colloid and can prevent altogether or simply delay the coagulation of $\text{Al}(\text{OH})_3$ in the presence of electrolytes or of other colloids with opposite charge. We have noted the fact that our soils contain abundant humus all the way down. Thus the conditions are present for most effective leaching downward of alumina in our soils, as is indicated by the chemical analyses.

It is true, however, that Aarnio, in an exhaustive study of the influence of humus-laden water on the formation of podsols in Finland (as recorded by Stremme²⁹), has demonstrated the fact that it requires appreciably more humus to prevent the coagulation of Al_2O_3 sols than it does to prevent the precipitation of Fe_2O_3 sols. Hence, under the same conditions for both, relatively less Al_2O_3 will be carried to greater depths than Fe_2O_3 . This fact is similarly indicated in the chemical analyses of our soils.

The greater amounts of alkali and alkali metals in the Banahao soil, as compared with the Malabar soil, easily accounts for the fact, noted before, that relatively less alumina has migrated downward in the Banahao soil than in the Malabar soil.

The field-criteria for determining whether podsolization takes place, are based on the changes in soil-colors due to the removal of iron oxides as the principal coloring matter. It is therefore justified to inquire more fully into the causes and mechanism of *iron oxide* migrations under the influence of humus-laden water.

The technical literature in various branches of science is full of theories that have attempted to explain the phenomena. Their great number suggests the importance that is attached to the problem from the side of geologists, petrologists, stratigraphers, soil-scientists, chemists, agronomists, engineers, etc.

The various theories may be conveniently grouped into the following three groups:

- (1) Theories based on molecular reactions,
- (2) Theories based on collòidal reactions,
- (3) Theories based on the action of micro-organisms.

Ad. 1.—According to Stremme (*op. cit.*, 17a, pp. 133–134) the German F. Senft was the first to clearly point out (1876) the molecular-chemical mechanism of the removal of iron by bog-waters, *i.e.*, by waters laden with organic matter or acid humus such as is the case in our soils. The following passage may here be quoted from Senft's book on "Rocks and Soils" (Munich, 1876):

"If weathering of these minerals (feldspars, micas, hornblende) takes place under the exclusion of air, or under the unhampered influence of water, laden with carbon dioxide or ammonia—as is namely the case when a rock surface has a thick cover of decaying vegetable matter—then all ferro-iron in feldspars, micas and hornblende is changed to iron bicarbonate or to ferroammonium compounds and is leached out as such by percolating water, as a result of which the clay-in-the-making is freed from all admixtures of iron oxide and of the ochre-yellow coloration it imparts, so that the clay finally becomes white in color. Upon further leaching of the alkali and alkali-earth metals this clay becomes kaolin."

This theory, modified as well as unmodified, has been adhered to by a great many prominent geologists and soil-students, such as Emeis, van Hise, Ramann. It is still being advocated by some, such as Stremme and Stahl in connection with the cause of the white color of kaolins and by Berg in connection with the origin of sedimentary iron-ore deposits.³⁰

Ad. 2.—The colloid theory of iron-migration, perhaps, originated some thirty years ago with the Dutch physical-chemist van Bemmelen, whose name will always be linked with the first systematic treatment of weathering processes as colloid-chemical phenomena. But according to Stremme again²⁹ the Russian agricultural chemist Gedroiz was the first (1908) to let colloid chemistry bear upon soil-formation proper with special reference to Fe, Al and Si.³¹ The three

elements start their migration as hydrosols of Fe_2O_3 , Al_2O_3 and SiO_2 respectively. These are fairly unstable and are easily precipitated as irreversible gels in the absence of organic matter. But when organic matter is present, which acts as a protective colloid, they may remain a long time as sols and thus be carried for great distances by the percolating water. These facts have been amply corroborated by subsequent workers, conversant with the teachings and methods of modern colloid chemistry.

Ad. 3.—According to Ransome it has been known since 1836 that certain bacteria have the power of withdrawing iron from solution and causing its precipitation as ferric hydroxide. A great many contributions have since been made to the knowledge of the action of organisms in the processes of transformation, migration and deposition of iron. These contributions have not only been made by biologists, but by geologists as well. E. C. Harder has recently given an able summary of this and related subjects to which reference may be made.³²

The writer confesses a preference for the colloid theories for reasons that need not be detailed here.

In the light of these theories, which have been amply substantiated by facts, the downward migration of iron in our particular soils is readily explained as being due, again, to the abundance of organic matter at all depths. This organic matter, acting as a protective colloid, enables the ferric hydroxide to remain a long time as a hydrosol, so that it can be carried downward for great distances in the percolating soil water before it is precipitated as an irreversible gel.

The question might be raised why the ferric hydroxide sols have not been gelled anywhere within visible depth to form a distinct layer of iron "hardpan" or iron-concretions, such as is often the case in true podsoles of the middle latitudes.

Anticipating the explanation, it may be suggested that, again, the abundance of organic matter at all depths has prevented the iron hydroxide from being precipitated in any one layer within the range of depths studied in the field.

Modern colloid chemistry teaches³³ that gelation of the hydrosol of an irreversible or lyophobic colloid, such as is colloidal ferric hydroxide, can take place only in two ways:

- (1) by neutralization of the charge,
- (2) by dehydration.

Ad. 1.—Complete neutralization of the charge is not likely to occur down to the investigated depths because of the large amounts of protective colloids all the way down. The amount of black matter or soluble humus is particularly significant in this respect; it is quite appreciable even at the lowest depth. Besides, the amount of bases has greatly decreased in the lower horizons, and hence will be still less effective as a possible flocculating agent.

A special case of flocculation by neutralization of the electrical charge is perhaps the following phenomenon, which has been intensively studied by Sahlbom.³⁴ When a strip of filter paper is hung into an aqueous solution of ferric hydroxide sol the water will rise to great height, but the ferric hydroxide is precipitated at the base and remains there. Sahlbom found that this generally happens with positive colloids flowing through capillary tubes of 0.15 mm. maximum diameter, and is independent of the chemical nature of the capillary medium. The phenomenon is due to the generation of electromotive forces by the flow of the dispersive medium in the capillaries. These electromotive forces bring about a discharge or neutralization of the positively charged colloidal particles and consequent precipitation.

It might be argued that this phenomenon should have given rise to "iron hardpans" in our soils. Even if the mechanical analysis show them to be sands, it is conceivable that the capillary openings between the individual soil-particles are less than 0.15 mm. in diameter, thus fulfilling the necessary conditions for the precipitation of the ferric oxide sols.

The fact is, however, that such a precipitation has not taken place and no "hardpans" were found anywhere to the

investigated depths. The explanation of this fact lies in the acidity of the soil-reaction. Sahlbom has namely found, also, that the addition of an acid caused the ferric oxide sol to rise in the capillary columns of the filter paper. This is partly due to the peptization of the precipitated gel and partly to a rise in the precipitation potential of the colloid. Thus the medium to strong acidity of our soils can well account for the lack of hardpan formation.

Ad. 2.—Dehydration is likewise improbable as a possible cause for the gelation of iron hydroxide sols in our soils because they are constantly moist to wet all the year around. They were found to be in that state even during a period of exceptional drought, as has been noted before. This circumstance, together with the prevailing low temperature all the year round, eliminates dehydration as a cause for the development of an "iron hardpan" or of iron oxide concretions in situ.

However, it has been pointed out in the discussion of the mineralogical analyses that reddish-brown grains of some partially hydrated iron oxide were found to prevail in the *B*-horizons of both soils. They were not found in the soils in situ. In consideration of the high contents of easily soluble iron oxide, as per the Demolon extraction, it is held that the grains have developed subsequently. In other words, owing to the unnatural desiccation to which the soils have been subjected once they were removed from their natural environment, the ferric hydroxide sols in situ have become gelated, by partial dehydration, to form the grains just spoken of.

This is a process to which van Bemmelen has ascribed the dehydration of hydrated ferric oxide under the natural conditions prevailing in hot tropical lowlands where laterites are developed.

Shaking for 24 hours in the ammoniated water used as a preliminary to the mechanical analysis, according to the United States Bureau of Soils method, did not seem to bring about the deflocculation of those grains. They may thus have masked the real texture of the soil.

These considerations should therefore caution one in the

interpretation of mechanical analyses of soils which contain large amounts of organic matter and ferric hydroxide, unless their original moisture condition has been preserved. The author is not aware that this point has ever been considered before, so that it may not be amiss to emphasize it here.

SUMMARY AND CONCLUSIONS

1. Field and laboratory studies were made to test the validity of the principles of the modern climatic classification of soils.

2. Specifically, the object was to ascertain whether podsoles are found, respectively whether podsolization takes place in tropical high altitudes, as the principles demand.

3. The field observations were made in the Oriental tropics.

4. The laboratory investigations were carried out on soil-profiles collected above 2,000 m. on the islands of Java (N. E. I.) and Luzon (P. I.).

5. Field and laboratory studies indicate that podsoles are not found in the high altitudes of the Oriental tropics, but that the process of podsolization does occur in much the same way as it occurs in the middle latitudes.

6. Minor differences of degree are pointed out and naturally accounted for.

7. The evidence lends support to the modern classification of soils as based on the climatic control of rock-weathering and soil-formation.

8. The mechanism of podsolization is discussed with special reference to the investigated soils.

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